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	Patents ADP number *(if you know it)*	~~54510003~~ 6812069003
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4.	Title of the invention	THREE-DIMENSIONAL IMAGING SYSTEM
5.	Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Mr Anthony Oliver Bowdery D/IPR (DERA) Formalities Poplar 2 MoD (PE) Abbey Wood #19 Stoke Gifford Bristol BS34 8JH
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DUPLICATE

Three-dimensional Imaging System

The current invention concerns a system for imaging simultaneously multiple layers within a three-dimensional object field and has applicability in fields including optical information storage, imaging short-timescale phenomena, microscopy, imaging three-dimensional object structures, passive ranging, wavefront analysis and millimetre wave optics.

Optical data storage media having an increased capacity by virtue of multiple layers of data are an area of increasing interest to the computer industry. One proposed solution is to read from multiple data layers by physically moving an objective lens to bring each layer into focus one layer at a time.

UK patent application GB 9804996.8 describes an invention for imaging, simultaneously, multiple layers within a three-dimensional field, by means of a quadratically distorted diffraction grating. One application identified for the technique was the reading of data from several layers of a multi-layer optical data storage medium simultaneously, with no moving parts.

In a high performance, near diffraction limited optical system such as a compact disk player, all sources of wavefront aberrations must be considered. In a standard compact disk, the data layer is covered with a substrate several hundred microns thick. Propagation of light through this substrate (which is essentially a parallel plate) introduces spherical aberration, increasing the spot size on the data layer and degrading resolution. This effect is overcome in conventional, single layer, compact disk systems by building spherical aberration correction into the objective lens.

In a multi-layer optical data storage medium the degree of spherical aberration is dependent on the depth of the data layer below the surface, hence when reading from each distinct layer a different level of spherical aberration correction is required. An aberration corrected objective lens is therefore not sufficient. Several patents on multi-layer optical data storage systems, which rely on a moving lens to focus at different depths, have suggested ways of performing 'active' spherical aberration correction. US 5202875 suggests using a stepped

block of substrate material which is moved across the optical beam (using a voice coil motor) to a position dependent on the layer being read, such that the thickness of material that the beam passes through is constant. Other suggestions include a pair of prisms, one which is translated, a rotating disk of variable thickness and movable compensation plat

All of these approaches introduce additional moving parts and complexity into the system.

According to this invention, an apparatus for producing substantially in-focus images in a common plane from a plurality of object planes comprises:

a diffraction grating capable of producing an image associated with each diffraction order and being substantially quadratically distorted so as to cause the images to be formed under various focus conditions and being further distorted so as to correct for spherical aberration of images associated with each object plane;

means for detecting two or more of the spatially-separated images

and imaging means, capable of directing radiation from the grating to the detecting means;

wherein the imaging means, diffraction grating and detecting means are arranged on an optical axis which intersects the object planes and the diffraction grating is located in a suitable grating plane.

In a preferred embodiment, the origin of the quadratic function is offset away from the optical axis.

In a further preferred embodiment, displacement of the origin of the quadratic distortion function causes alignment along the optical axis of the images associated with each diffraction order. One object plane may contain an illumination source.

GB 9804996.8 describes the use of a distorted diffraction grating to image multiple object planes simultaneously, allowing simultaneous read out from several layers within a multi-

layer structure. This is achieved using a grating distorted as a quadratic function of radius from the optical axis, which effectively generates a different focal length system in each diffraction order.

The current invention shows that by including suitable terms in the grating distortion function the spherical aberration associated with each data layer can be eliminated automatically, with no moving parts, and that by offsetting the origin of the quadratic function away from the optical axis, the position of the diffraction orders can be controlled.

The examples described herein illustrate the use of distorted diffraction gratings to correct spherical aberration in systems which also use distorted diffraction gratings to produce images from different object planes. However, it will be obvious to a person skilled in the art that the techniques described herein are equally applicable to other systems in which correction of spherical aberration for different object planes would be beneficial including, but not limited to, other systems in which data is read from multiple layers of a data storage medium.

The invention will now be described with reference to the following figures in which:

figure 1 illustrates reading of data from a multi-layer structure using a distorted diffraction grating;

figure 2 shows a comparison of phase profiles and grating structures for gratings with defocus, spherical aberration and both built in;

figure 3 shows qualitatively image cross-sections associated with -1, 0 and +1 diffraction orders through a grating with ${}_0C_{40}=1\lambda$;

figure 4 shows image intensity cross-sections of point sources on layers corresponding to 7, 6 and 5 of figure 1 with defocus only (left hand column) and defocus and spherical aberration (right hand column) corrected gratings;

figure 5 shows a quadratically distorted diffraction grating with ${}_0C_{20} = 4\lambda$ and an offset of the quadratic function relative to the optical axis of $x_0=\lambda r^2/(2\ d\ {}_0C_{20})$;

figure 6(a) illustrates the desired illumination of multiple layers in an object field and figure 6(b) illustrates illumination of such layers using gratings of the type shown in figure 2 and

figure 7 is a schematic diagram of a multi-layer optical data storage read head;

figure 8(a) shows schematically a conventional, undistorted, amplitude-only diffraction grating used in an imaging system and figure 8(b) shows the zero, +1 and -1 diffraction order images produced when such a grating is inserted in a suitable grating plane of an imaging system;

figures 9a and 9b illustrate respectively an undistorted grating and the distortion of a grating by a fixed amount, Δ;

figure 10 shows schematically a simple system for producing multiple images associated with the various diffraction orders of a grating;

figure 11 shows two computer generated amplitude gratings;

figure 12 shows experimental measurements of the images of a resolution target formed in the +1, 0 and -1 diffraction orders of a quadratically distorted diffraction grating;

figure 13(a) shows crossed amplitude gratings, figure 13(b) shows the defocus states of the corresponding diffraction orders and figure 13(c) shows a computer simulation of the image of a point source through the grating structure of figure 13(a);

figure 14 shows schematically a simple imaging system using a quadratically distorted diffraction grating to produce in-focus images of different object planes at a single detector plane;

figure 15 shows images of an extended pinhole obtained by experiment using a quadratically distorted amplitude grating;

The wavefront aberration function (W_{SA}) known as spherical aberration can be written as,

$$W_{SA}(r) = \underbrace{{}_0C_{40}\, r^4}_{\text{primary}} + \underbrace{{}_0C_{60}\, r^6}_{\text{secondary}} + {}_0C_{80}\, r^8 + \ldots \qquad \text{Equation 1}$$

where r is the distance from the optical axis. Primary spherical aberration (${}_0C_{40}$) is the dominant term but higher order terms may also need to be considered for high performance optical data storage systems. For a beam entering a parallel plate of refractive index n, with zero tilt, the primary and secondary coefficients of spherical aberration are given by,

$${}_0C_{40} = \frac{(n^2-1)}{8n^3}\, d\,(NA)^4 \qquad {}_0C_{60} = \frac{(n^4-1)}{16n^5}\, d\,(NA)^6 \qquad \text{Equation 2}$$

where d is the depth at which the beam is focused and NA is the numerical aperture of the beam (J Braat, 'Analytical expressions for the wave-front aberration coefficients of a tilted plan-parallel plate', Applied Optics. Vol.36, No.32, 8459,1998.). The linear dependence of spherical aberration on depth (d) means that all of the terms in equation 2 can be corrected with a suitably distorted diffraction grating. In the following discussion only the ${}_0C_{40}r^4$ term of equation 2 is considered, for clarity.

Referring to figure 1, optical system 1 is designed to image the central layer 6 within a multi-layer structure 11. A quadratically distorted grating 4, designed with a wavefront coefficient of defocus (${}_0C_{20}$), can be introduced such that the -1 diffraction order (associated with a defocus of $-{}_0C_{20}$) is focused on layer 7, the +1 diffraction order (associated with a defocus of $+{}_0C_{20}$) is focused on layer 5 and the zero order remains focused on Layer 6.

Thus images of planes 5, 6 and 7 associated with diffraction orders +1, 0 and -1 are produced on plane B.

To eliminate spherical aberration the optical system 1 (without grating) can be designed to correct for the spherical aberration introduced on the beam focused on layer 6, as in a standard 1-layer compact disk read head. A diffraction grating distorted according to r^4 then be designed with a wavefront coefficient of spherical aberration (${}_0C_{40}$), such that the -1 diffraction order (associated with a spherical aberration correction of $-{}_0C_{40}$) is spherical aberration corrected for layer 7, the +1 diffraction order (associated with a spherical aberration correction of $+{}_0C_{40}$) is corrected for layer 5 and the zero order remains spherical aberration corrected for layer 6.

Table 1 shows the defocus and spherical aberration (first order only) terms, associated with each layer 5, 6 and 7 introduced into grating 4.

Table 1

Layer	Diffraction Order	Grating Correction (Defocus)	Grating Correction (Spherical Aberration)
7	-1	$-{}_0C_{20}$	$-{}_0C_{40}$
6	0	0	0
5	+1	$+{}_0C_{20}$	$+{}_0C_{40}$

The complete grating must incorporate both defocus and spherical aberration correction and will be distorted according to,

$$\Delta(x,y) = \frac{d}{\lambda}\left[\frac{(x-x_0)^2+(y-y_0)^2}{r^2}\ {}_0C_{20} + \frac{(x^2+y^2)^2}{r^4}\ {}_0C_{40} + \frac{(x^2+y^2)^3}{r^6}\ {}_0C_{60} + \text{higher order terms}\right]$$

Equation 3

where D(x,y) is a distortion in a direction perpendicular to the grating lines, d is the grating period, r is the radius of the grating aperture and x and y are Cartesian coordinates relative to an origin on the optical axis in the plane of the grating. x_0 and y_0 represent an offset of the origin of the quadratic distortion function from the optical axis of the system. Exploitation of such an offset is described later. Offsets of the spherical aberration terms in equation 2 (${}_0C_{40}$,

${}_0C_{60}$ and higher terms) can not be exploited in the same manner and are not included in equation 3. Such distortion functions should be centred on the optical axis.

The grating distortion D(x,y) introduces a phase shift of,

$$\phi(x,y) = \frac{2\pi m \Delta(x,y)}{d}$$

Equation 4

onto the wavefront scattered from the grating into the m^{th} diffraction order.

As an example, the level of spherical aberration to be corrected can be estimated by assuming a multi-layer optical storage medium with a refractive index of 1.5806 at a wavelength of 650nm, a numerical aperture of 0.60 and layer separations of 100µm. These parameters give additional spherical aberration of ${}_0C_{40}$=0.95λ and ${}_0C_{60}$ =0.24λ from layer to layer (equation 2). (J Braat, 'Analytical expressions for the wave-front aberration coefficients of a tilted plan-parallel plate', Applied Optics. Vol.36, No.32, 8459,1998.).

Figure 2 compares the phase profiles and grating structures for gratings with defocus only (a), spherical aberration only (b) and defocus and spherical aberration (c) built in. The most visible difference is in the greater concentration of grating distortion away from the mask centre with spherical aberration rather than with defocus only.

The ability of a grating distorted according to r^4 to generate spherical aberration of equal magnitude but opposite sign in the +1 and −1 diffraction orders has been demonstrated in computer simulations. The simulation modelled a wavefront with specified levels of spherical aberration, incident on grating (b) of Figure 2. Figure 3 shows that when a wavefront aberration with one wave of spherical aberration is used, the +1 diffraction order is corrected, whereas when a wavefront with one wave of spherical aberration of opposite sign is used, the −1 diffraction order is corrected.

The Y (vertical) axes in figures 3 and 4 represent intensity and the X (horizontal) axes represent distance along a line through the image formed.

The operation of a grating with built-in defocus and spherical aberration correction has also been demonstrated with computer simulations. With reference to Figure 1, consider an optical system focused and spherical aberration corrected for layer 6. Layers 7 and 5 are located approximately 100 x 10^{-6}m either side of layer 6, associated with additional defocuses of, say, plus and minus one wave and additional spherical aberration of, say, plus and minus one wave. Point sources are located on each of the three planes. A grating with a purely quadratic distortion function (${}_0C_{20}=1\lambda$, ${}_0C_{40}=0$), designed to focus the diffraction orders on layers 5, 6 and 7 (in the +1, 0 and −1 diffraction orders respectively) produces the image cross-section shown in the left hand column of Figure 4. The images of the point sources on layers 7 and 5 are enlarged and reduced in intensity due to the uncorrected spherical aberration. A grating designed with defocus and spherical aberration correction (${}_0C_{20}=1\lambda$, ${}_0C_{40}=1\lambda$) produces the image cross-section shown in the right hand column of Figure 4. The spherical aberration is now corrected for all data layers and the images of the point sources are in focus and of diffraction limited size.

Shift of Quadratic Distortion Origin

Consider an undistorted grating (${}_0C_{20} = {}_0C_{40} = {}_0C_{60} = 0$) consisting of parallel strips of different transmissivity, reflectivity or optical thickness. The y-axis is defined to be parallel to the strips in the grating and the x-axis to be perpendicular to the strips. A plane wavefront incident normally on the grating is diffracted into orders at angles θ_m to the optical axis where,

$$\sin\theta_m = \frac{m\lambda}{d} \qquad \text{Equation 5}$$

The angular deflection of each order is equivalent to introducing onto the incident wavefront a phase tilt of,

$$\phi(x,y) = \frac{2m\pi x}{d} \qquad \text{Equation 6}$$

across the grating plane.

When ${}_0C_{20}$ is non-zero the expansion of the defocus (first) term in equation 3 produces a phase shift given by,

$$\phi(x,y) = {}_0C_{20}\left[\frac{2\pi m}{r^2\lambda}(x^2+y^2) - \frac{4\pi m x_0}{r^2\lambda}x - \frac{4\pi m y_0}{r^2\lambda}y + \frac{2\pi m(x_0^2+y_0^2)}{r^2\lambda}\right]$$

Equation 7

The first term in equation 7 is the defocus term that would be obtained from a grating distorted according to a quadratic function centred on the optical axis. Shifting the origin of the quadratic function therefore has no effect on the level of defocus introduced into each diffraction order.

The final term in equation 7 represents a dc phase offset which has no effect on the wavefront shape diffracted into each order but which may have some implications for coherent detection schemes.

The second term in equation 7,

$$\phi(x,y) = -\frac{4m\pi}{\lambda r^2}\,{}_0C_{20}\; x_0\; x \qquad \text{Equation 8}$$

represents a linear increase in phase across the x-axis of the grating plane. This phase tilt has the effect of changing the separation of the grating diffraction orders, whilst leaving the position of the zero order (m=0) and level of defocus unchanged. If x_0 is chosen to have a value of ,

$$x_0 = \frac{\lambda r^2}{2d\,{}_0C_{20}} \qquad \text{Equation 9}$$

then the phase term (equation 8) becomes equal to,

$$\phi(x,y) = \frac{-2m\pi x}{d} \qquad \text{Equation 10}$$

This phase tilt is equal and opposite in sign to that introduced into light scattered from the gating structure. The cancellation of these two terms (equation 6 and equation 10) for each order causes the diffraction order spacing to become zero in a plane perpendicular to the

optical axis, corresponding to all of the orders lying along the optical axis of the system. The diffraction orders remain spatially separated along the optical axis according to the level of defocus (${}_0C_{20}$) within the distorted grating. The shift of the origin of the quadratic funct to that defined in equation 9 leads to a grating structure consisting of circular fringes, as shown in Figure 5. This form of grating is used as part of an illumination system described below.

When ${}_0C_{20}$ is non-zero a shift of the origin of the quadratic function in the y-direction (i.e. finite y_0 in Equation 3) introduces a phase term,

$$\phi(x,y) = -\frac{4m\pi}{\lambda r^2}\,{}_0C_{20}\;y_0\;y \qquad \text{Equation 9}$$

which is a linear increase in phase across the y-axis of the grating plane. This causes the diffraction orders (other than m=0) to move along the y-direction in the image plane.

Through choice of x_0 and y_0, the position of a particular diffraction order in the image plane can be controlled, whilst leaving the level of defocus and spherical aberration unchanged.

Illumination System

In order to achieve maximum possible resolution and storage density each layer in a multi-layer data storage medium must be illuminated with a diffraction limited spot. Figure 6a shows the distribution of light that must be achieved from the source 13. In currently proposed systems with a moveable lens (US 5202875), the illumination uses the same optics as the read system. The illumination is focused at the right depth but needs additional spherical aberration correction.

The distorted grating described thus far and shown in Figure 2, images three on-axis objects onto three spatially separated image positions (Figure1). If the same grating is used in an illumination system, with a single illumination source, the spots of illumination are focused on the correct layers but are laterally displaced as shown in Figure 6b. Such a grating cannot therefore be used for both illumination and reading from a multi-layer structure.

However, using the techniques described in this specification and in GB 9804996.8, shifting the origin of the quadratic distortion function along the x-axis, through the parameter x_0 in Equation 3, allows the diffraction orders to be aligned along the optical axis. A grating of this type (Figure 5), incorporated into optical system 1 of Figure 6b would produce the desired illumination shown in Figure 6a. If the grating were additionally distorted to include the spherical aberration terms in Equation 3 then the system would illuminate each data layer as shown in Figure 6a with automatic spherical aberration correction. This ability has been demonstrated in computer simulations.

Complete System

Using two gratings of the type described in this invention a complete system for illumination and reading from a multi-layer optical data storage medium, with no moving parts and automatic spherical aberration correction can be described. The system is shown schematically in Figure 7. Light from the source 13 passes through a grating 4b of the type described in the paragraph above (and Figure 5), which produces multiple on-axis, spherical aberration corrected foci corresponding to the different data layers 5, 6 and 7. Light reflected from the data layers passes through a grating 4a of the type shown in Figure 2c with spherical aberration correction, which produces spatially separated images of the different data layers on plane B. It is well known that a polarisation sensitive beamsplitter and polarisation rotating plates can be used to minimise losses in such a system. Numeral 1 is used generally to designate an optical system.

GRATING DESIGN

The design of distorted gratings for imaging simultaneously multiple layers within a three-dimensional object field, as used in the invention of GB 9804996.8 (i.e. without spherical aberration correction), is described here for convenience.

A standard one-dimensional diffraction grating consists of alternate regularly spaced strips of different transmissivity, reflectivity or optical thickness. When the grating is used within an imaging system, multiple diffraction orders appear in the image plane in addition to the unscattered zero order. Each diffraction order contains the same information about the object field as the zero order, though with different levels of intensity dependent on details of the

grating construction. Figure 8 shows, as an example, a one-dimensional amplitude grating and the images of a point object formed in the −1, 0 and + 1 diffraction orders.

If the grating geometry is distorted locally, by a displacement of the strips in a direction perpendicular to their long axis, a phase shift is introduced in the wavefront scattered from the distorted region, the level of which is dependent on the amount of local distortion of the grating relative to its undistorted form. The level of local phase shift is related to the distortion of the grating through equation 1,

$$\phi = \frac{2\pi m\Delta}{d} \qquad \text{Equation 10}$$

where d is the grating period, m is the diffraction order into which the wavefront is scattered and Δ is the distortion of the grating strips relative to their undistorted position, as shown in figure 9. Such a distortion of the grating produces phase shifts of equal magnitude but opposite sign in the wavefronts scattered into +1 and −1 diffraction orders and leaves the unscattered wavefront in the zero order unaltered.

It is important to note that this technique allows continuous phase values to be encoded using a binary (two level) grating, although the invention can also be applied to multiple or continuous level gratings.

For applications using computer-generated holograms, the distorted grating can be designed by dividing the grating area into a number of cells, which can be of any space-filling shape, and calculating the degree of distortion to be applied to the grating for each cell individually. Alternatively the distortion can be applied to the grating as a whole leading to continuously distorted strips. Both of these approaches can be implemented using computer design followed by grating fabrication or by using an electrically addressed liquid crystal or other electro-optic device.

For non-digital production methods an alternative technique is to record holographically the distorted fringe pattern into an optically sensitive medium, or to use an optically programmable liquid crystal device to allow the grating to be changed in real-time.

The above descriptions refer to arbitrary distortions that could be used to generate arbitrary phase changes on the wavefront scattered into a selected diffraction order.

Below are described the grating distortions required to produce the defocus effects required for imaging of multiple layers within a three dimensional object field.

Defocus Gratings

A defocused optical system has a phase shift which, compared to an in-focus image, can be represented by a quadratic function of the distance from the optical axis and measured relative to the Gaussian reference sphere (e.g. section 5.1, Principles of Optics, Born & Wolf, Pergammon, Edition 6, Oxford, 1980). This invention relates to a diffraction grating distorted as a quadratic function of distance from the optical axis of the system according to,

$$\Delta(x,y) = \frac{{}_0C_{20}d}{\lambda r^2}(x^2 + y^2) \qquad \text{Equation 11}$$

where $\Delta(x,y)$ is a distortion in a direction perpendicular to the grating lines (figure 9), x and y are Cartesian co-ordinates relative to an origin on the optical axis in the plane of the grating, d is the grating period, λ is the optical wavelength, ${}_0C_{20}$ is the degree of defocus introduced into the image formed in the +1 diffraction order (${}_0C_{20} \geq 0$) and r is the radius of

the grating aperture which is centred on the optical axis. In equation 11 a circular aperture has been assumed, but the invention can be applied to an aperture of any shape. ${}_0C_{20}$ is the wavefront coefficient of defocus of the grating (the traditional defocus aberration const[illegible] equivalent to the pathlength difference introduced at the edge of the aperture between, in this case, the wavefront scattered into the +1 diffraction order and the Gaussian reference surface for that diffraction order {e.g. section15-5, Geometrical and Physical Optics, R S Longhurst, Longman, Edition 3, London, 1973}). The phase change imposed on the wavefronts scattered into the various diffraction orders can be calculated by combining equation 10 and equation 11 to give,

$$\phi(x, y) = m\frac{2\pi\, {}_0C_{20}}{\lambda r^2}(x^2 + y^2) \qquad \text{Equation 12}$$

This quadratic phase shift, introduced by the grating, leads to a defocus of all diffraction orders other than the zero order. The magnitude and sign of the defocus is dependent on the diffraction order (m). Thus a series of images of the object field with differing defocus conditions is produced simultaneously and side-by-side on the detector in the different diffraction orders.

The principle of the invention can be demonstrated with reference to the −1, 0 and +1 diffraction orders. Referring to figure 10, the defocusing effect of a quadratically distorted grating can be demonstrated using an optical system (1), designed and arranged to image an object (2) on the optical axis (3) onto detector plane B at the normal focal plane of the optical system.

A quadratically distorted diffraction grating (4) which is added to the optical system (1) produces two additional images of the object (2) in plane B in its +1 and −1 diffraction orders. In the normal focal plane B the zero order image remains in focus, whilst the images in the +1 and −1 diffraction orders undergo defocus of equal magnitude but opposite sign. If the detector is moved along the optical axis either side of plane B, a plane can be reached where the physical defocus cancels out the defocus introduced by the grating into the

diffraction orders. In this way the images in the +1 and −1 diffraction orders can be brought in to focus (planes A and C).

The separation δ_i of the image planes A, B and C is determined by the grating distortion, the radius of the grating aperture and the optical system through,

$$\delta_i \approx \frac{2v^2 m\ {}_0C_{20}}{2vm\ {}_0C_{20} + r^2} \qquad \text{Equation 13}$$

where r is the grating aperture radius, v is the distance from the normal image plane (B) to the secondary principle plane of the optical system, and the approximation v >> r (v is much greater than r) has been made. Terms of higher order in v and r can be used in cases where v is not much greater than r. Note that if a grating is designed with defocus represented by ${}_0C_{20} = n\lambda$, then the +1 diffraction order undergoes a defocus equivalent to $n\lambda$, the −1 diffraction order will undergo a defocus equivalent to $-n\lambda$ and, through equation 13, planes A and C will be located either side of and at different distances from plane B.

In the case where $2vm_0C_{20} << r^2$, equation 13 can be approximated by,

$$\delta_i \approx 2m\left(\frac{v}{r}\right)^2 {}_0C_{20} \qquad \text{Equation 14}$$

and planes A and C are symmetrically placed about plane B.

Equation 13 can be rearranged in terms of the grating defocus (${}_0C_{20}$) needed to generate the required image plane separation (δ_i) between in-focus images in the zero and +1 diffraction orders (m=1),

$${}_0C_{20} = \frac{r^2\delta_i}{2v(v-\delta_i)} \qquad \text{Equation 15}$$

Figures 11(a) and 11(b) each show examples of gratings with spherical apertures and distorted as a quadratic function of distance from the centre, to give different levels of defocus, for figure 11(a), ${}_0C_{20}=\lambda$ and for figure 11(b), ${}_0C_{20}=2\lambda$. These represent two

examples of many possible grating structures and were designed by computer as binary amplitude gratings using a square design cell.

Imaging a single object through a one dimensional defocusing grating – Experimental Results

In order to verify the defocusing properties, a grating was fabricated by photographically reducing an enlarged black and white picture of the appropriate pattern on to a 35mm slide. This provided a grating with a circular aperture of diameter 1cm, ${}_0C_{20}=\lambda$ and a grating period of 400 x 10^{-6}m (400μm). The optical system comprised two lenses with focal lengths of 50cm and 100cm, separated by 5cm. The object, a standard resolution target, was placed one focal length (50cm) in front of the first lens and the detector was placed one focal length (100cm) behind the second lens. A white light source was used to illuminate the object in transmission and the grating was placed between the two lenses in the region where the light was collimated. A filter with a bandpass of 10nm, centred at 650nm, was placed in front of the CCD detector used to record the image.

These parameters lead to an axial focal shift of +4.9cm and –5.5cm in the +1 and –1 diffraction orders respectively (equation 13). Figure 12 shows the images obtained upon location of the detector at positions corresponding to planes A, B and C of figure 10. The figure shows the raw images captured by the detector and the same images after processing to increase the intensities of the +1 and –1 diffraction orders (normalised), to aid observation. It can be seen that the –1, 0 and +1 diffraction orders are brought into focus as the detector is scanned along the optical axis of the system. At these positions, the physical defocus is cancelling out the wavefront deformations introduced by the gratings, that is the grating is introducing the quadratic variation of phase (defocus) predicted.

Imaging a single object through a two-dimensional defocus grating

The techniques described so far can be extended by using two-dimensional or multiple crossed one-dimensional gratings. If two gratings are crossed at right angles, the central nine diffraction orders can be usefully used. If the defocuses (${}_0C_{20}$) of the two crossed grating are chosen to be $a\lambda$ and $b\lambda$ then, for $|a-b| \neq a \neq b$, the nine images of the scene that are formed in parallel correspond to nine different defocus conditions. Figure 13a shows an example of

two crossed gratings having defocuses of $_0C_{20}=1\lambda$ and $_0C_{20}=1.5\lambda$, figure 13b shows the relative defocuses of the central nine diffraction orders and figure 13c shows a computer simulation of the image of a point source through the gratings (normalised). The image of the object in each diffraction order can be brought separately into focus by movement of the detector along the axis.

Imaging multiple object planes through a one-dimensional defocus grating

The function of the defocus grating can be considered in a different way. Referring to figure 14, if the detector is placed at image plane B, then the three images formed correspond to in-focus images of three different object planes 5, 6 and 7. The zero order will be the sum of the out-of-focus images of objects 5 and 7 and an in-focus image of object 6. If the degree of defocus is sufficient, a good image of object 6 will result. Similarly, objects 5 and 7 are discernible in the +1 and -1 diffraction orders. The grating therefore generates, side-by-side, simultaneous images of three different object planes at a single detector plane. The separation (δ_0) of the object planes imaged in plane B is determined by the grating distortion, the radius of the grating aperture and the optical system through,

$$\delta_o \approx \frac{2u^2 m\ {}_0C_{20}}{2um\ {}_0C_{20} + r^2} \qquad \text{Equation 16}$$

where $_0C_{20}$ is the wavefront coefficient of defocus of the grating for the +1 diffraction order, r is the grating aperture radius, m is the diffraction order, u is the distance from the central object plane to the primary principle plane of the optical system, and the approximation u >> r has been made.

The resolution in depth, in terms of the minimum separation of planes in the object field that can be individually imaged, is dependent on the depth of focus of the optical system being used. The image quality obtained when using a distorted diffraction grating to image multiple planes within the object field will be the same as if a 'through focal series' were obtained by adjusting the optical system to adjust its focus to image the same planes.
The fact that different object planes are imaged into different diffraction orders was first observed using a fixed detector and a single moveable object. Figure 15 shows images

obtained on locating a 400 x 10^{-6}m (400μm) diameter pinhole at positions corresponding to object planes 5, 6 and 7 of figure 14. The optical system comprised two lenses with a focal lengths of 50cm and 100cm, separated by 5cm, a CCD detector fixed at 100cm from the second lens (plane B) and a grating with an aperture diameter of 1cm, ${}_0C_{20}=\lambda$ and a period 400 x 10^{-6}m (400μm). Object plane 6 corresponded to a plane 50cm from the first lens and the grating parameters produced in-focus images in its −1 and +1 diffraction orders of object planes displaced by +1.3cm and −1.3cm relative to plane 6.

<u>Grating Location</u>

In a system in which converging and/or diverging beams exist, a suitable grating plane would be any plane that is normal to the optical axis and close to a lens other than a lens positioned in the image or object field, for example plane P1 in figure 16(i). In a system where a collimated beam is produced, a suitable grating plane would be any plane that is normal to the optical axis of the system and in the region in which the beam is collimated, for example anywhere between planes P1 and P2 in figure 16(ii), or a plane described as a suitable grating plane for a system with converging or diverging beams.

CLAIMS

1. An apparatus for producing substantially in-focus images in a common plane from a plurality of object planes comprising:

a diffraction grating capable of producing an image associated with each diffraction order and being substantially quadratically distorted so as to cause the images to be formed under various focus conditions and being further distorted so as to correct for spherical aberration of images associated with each object plane;

means for detecting two or more of the spatially-separated images

and imaging means, capable of directing radiation from the grating to the detecting means;

wherein the imaging means, diffraction grating and detecting means are arranged on an optical axis which intersects the object planes and the diffraction grating is located in a suitable grating plane.

2. An apparatus according to claim 1 whereby the origin of the quadratic distortion of the diffraction grating is displaced from the optical axis.

3. An apparatus according to claims 1-2, whereby the origin of the quadratic distortion function is displaced to cause alignment along the optical axis of the images associated with each diffraction order.

4. An apparatus according to claims 1-3 whereby one object plane contains an illumination source and the common plane is aligned along the optical axis.

Abstract

Apparatus for producing images simultaneously, in a common plane, from a plurality of object planes, and correcting for spherical aberration, by means of a distorted diffraction grating.

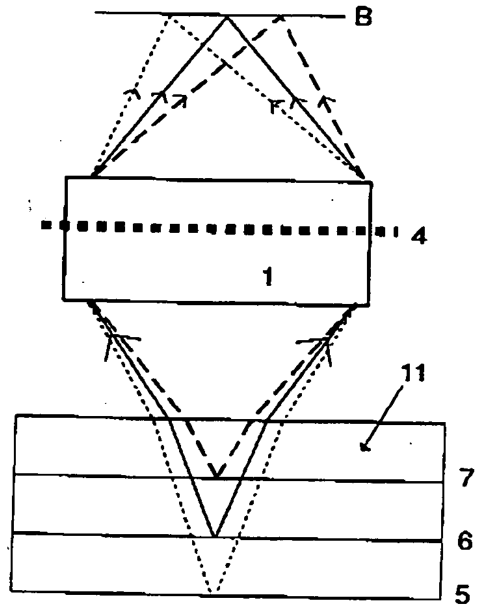


Figure 1

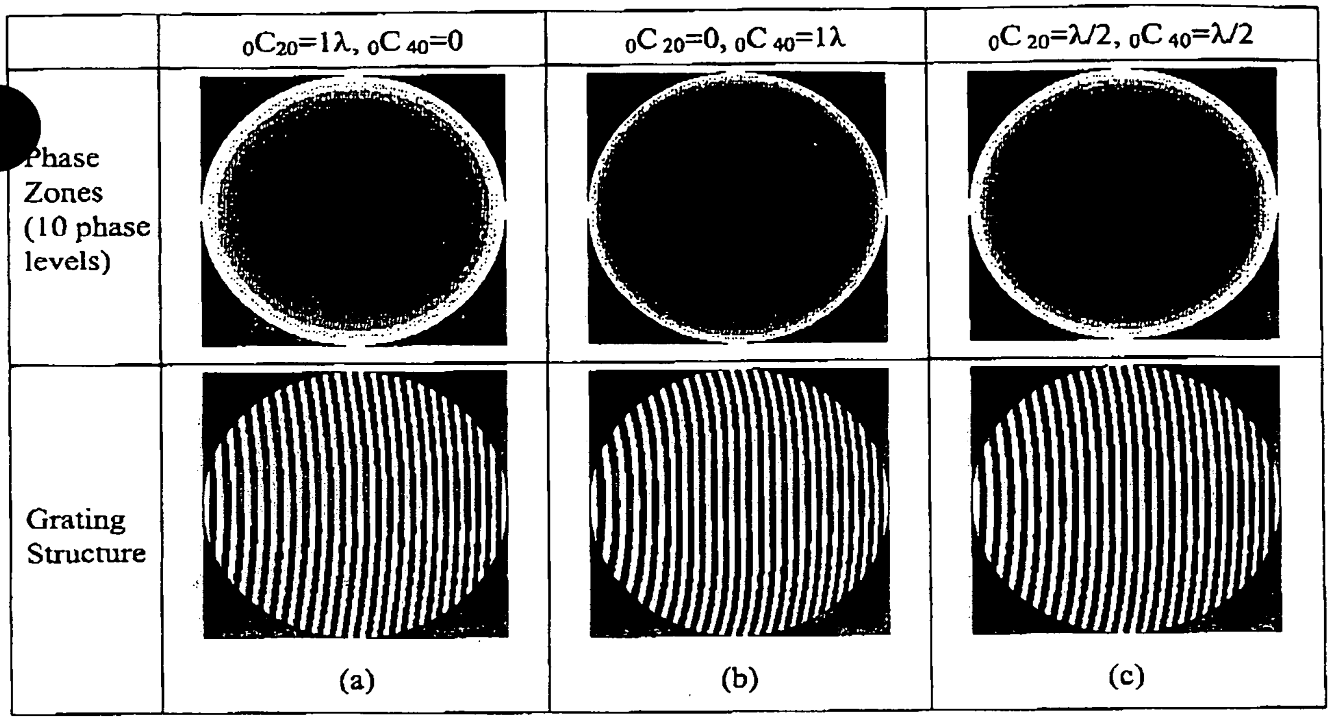

$_0C_{20}=1\lambda$, $_0C_{40}=0$
$_0C_{20}=0$, $_0C_{40}=1\lambda$
$_0C_{20}=\lambda/2$, $_0C_{40}=\lambda/2$
Phase Zones (10 phase levels)
Grating Structure
(a)
(b)
(c)

Figure 2

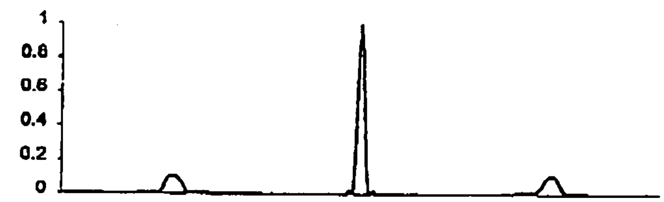
Wavefront Aberration	Image
${}_0C_{40}= -1\lambda.$	
${}_0C_{40}=0$	
${}_0C_{40}= +1\lambda.$	

Figure 3

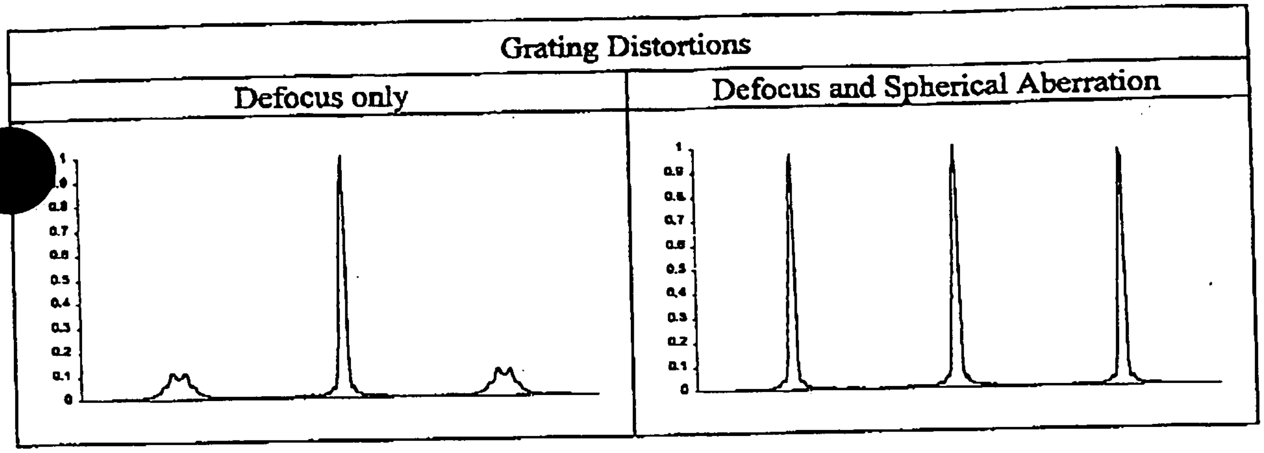

Grating Distortions
Defocus only
Defocus and Spherical Aberration
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure 4

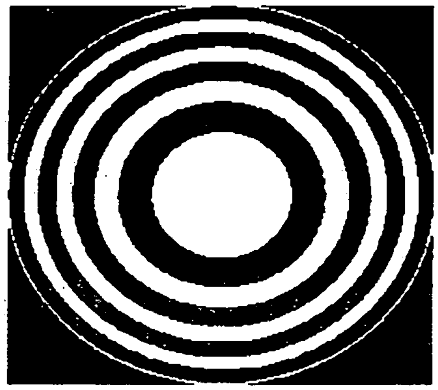
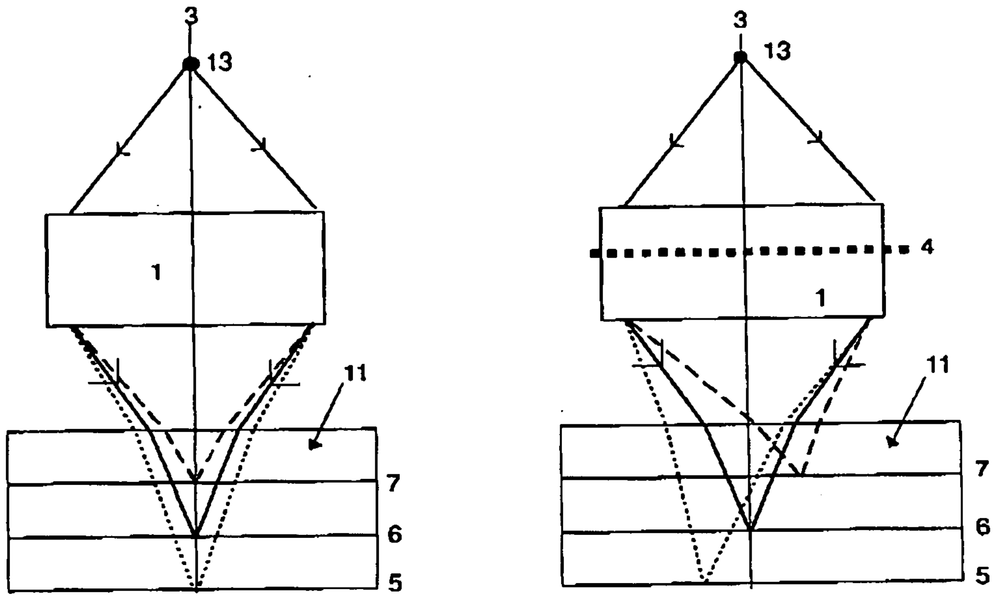


Figure 5



(a) (b)

Figure 6

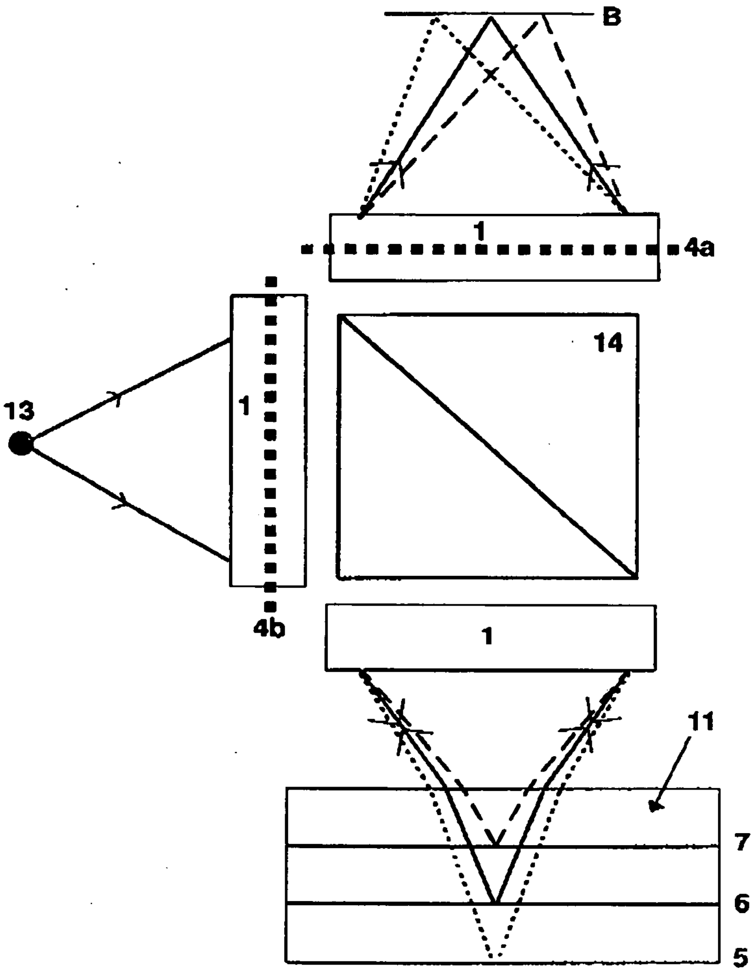


Figure 7

(a) (b)

Figure 8

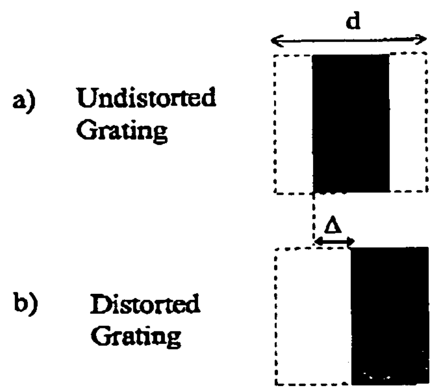


Figure 9

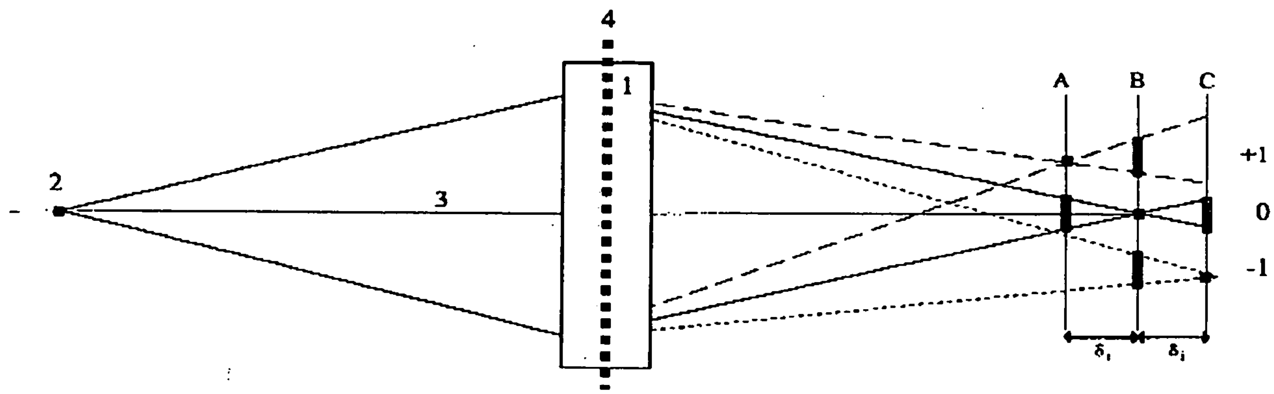
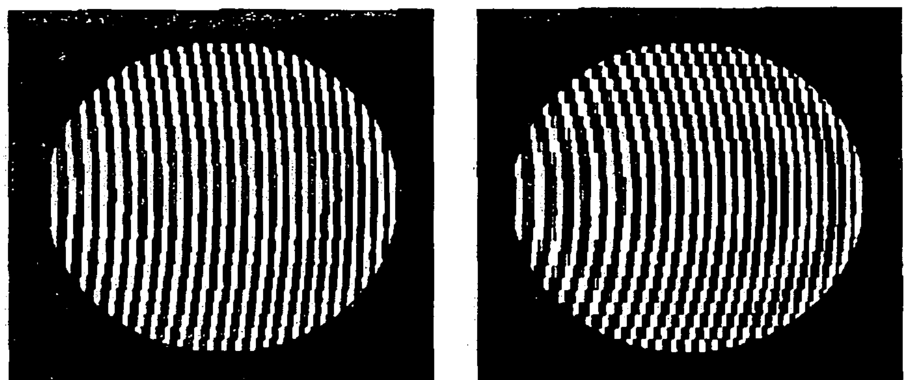


Figure 10



(a) (b)

Figure 11

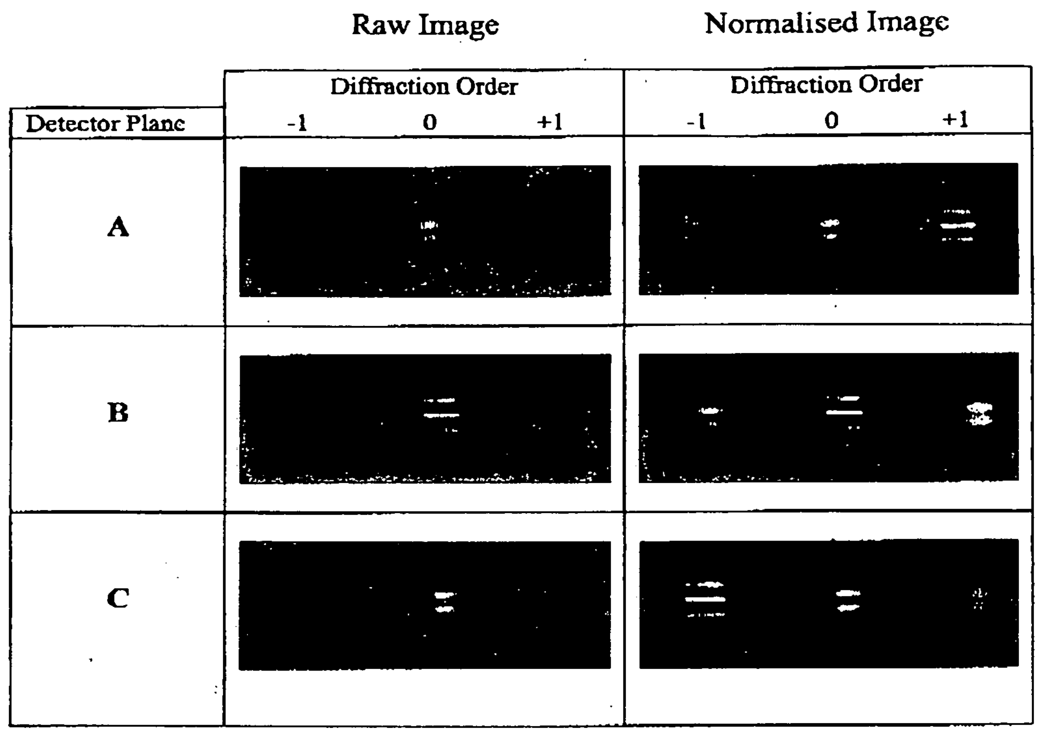

Raw Image
Normalised Image
Diffraction Order
Diffraction Order
Detector Plane
-1
0
+1
-1
0
+1
A
B
C

Figure 12

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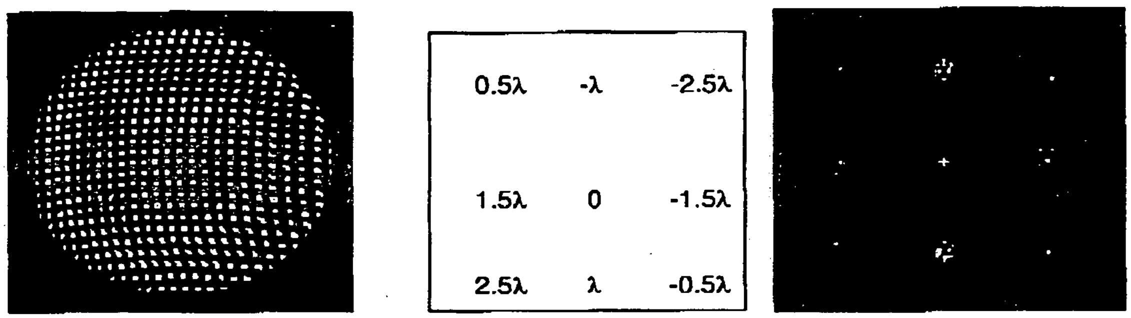


(a) (b) (c)

Figure 13

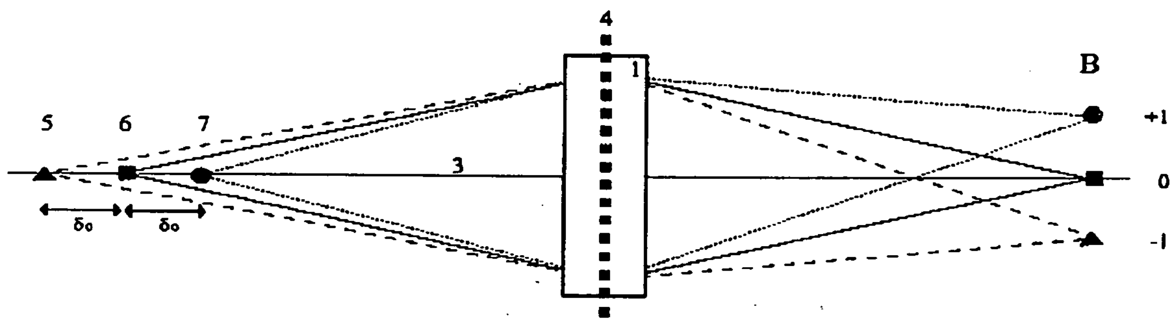


Figure 14

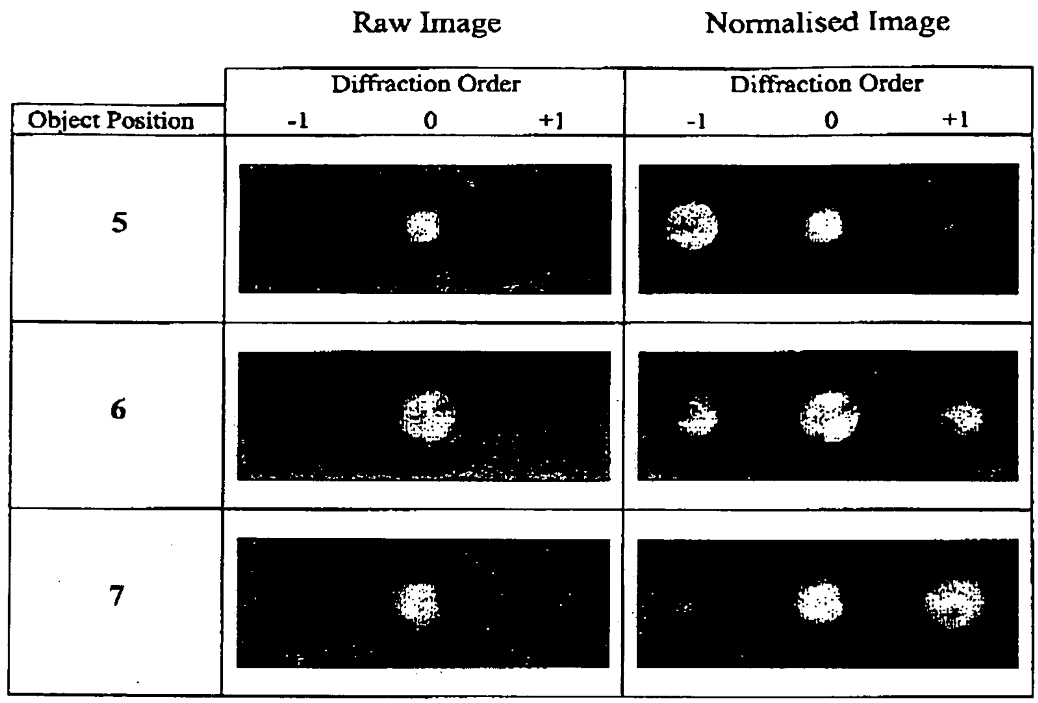
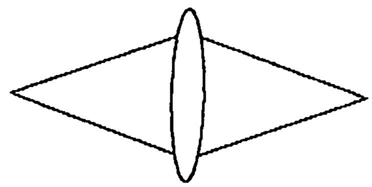

Raw Image
Normalised Image
Diffraction Order
Diffraction Order
Object Position
-1
0
+1
-1
0
+1
5
6
7

Figure 15

i)



ii)

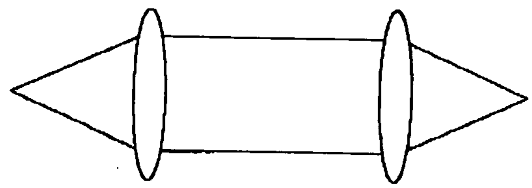


Figure 16

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5/3/99.

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